MODELING WATER PARCEL AGE AND PHYTOPLANKTON GROWTH IN THE HUDSON RIVER ESTUARY UNDER CLIMATE-INFLUENCED DISCHARGE CONDITIONS

A Thesis

Presented to the Faculty of the Graduate School

of Cornell University

in Partial Fulfillment of the Requirements for the Degree of

Master of Science

By

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ABSTRACT

The Hudson River is one of the most nutrient loaded rivers in the United States; however, phytoplankton production is relatively low and major blooms seldom if ever occur, possibly as a result of how quickly water moves though the Hudson River Estuary (HRE). Slower water residence times, which is expected to occur in future decades as a result of lower summer discharge rates, may then allow for significant phytoplankton growth. Light conditions also play a large role in determining phytoplankton growth in the HRE; the photic zone in the estuary is typically within 5 meters, relatively shallow compared to New York Harbor. This study involved using the Regional Ocean Modeling System (ROMS) to simulate idealistic HRE conditions for set discharge rates, in which a simple tracer was implemented to simulate phytoplankton growth and additional tracers were used to simulate age, a proxy for residence time. Growth of marine species was determined based off of salinity, light availability, and time spent within the estuary. In situ light attenuation and suspended matter data from Haverstraw Bay in the HRE was used to create a simple linear model, which is used to predict light attenuation coefficients based on suspended sediment concentration. Model results indicated that while phytoplankton growth increased as discharge rate decreased, extensive phytoplankton blooms were unlikely to occur under any realistic river conditions, as increased mixing and diminishing water column stratification associated with slower discharge rates appeared to counteract the favorability of increased residence times.

BIOGRAPHICAL SKETCH

Samuel Nadell grew up in Yorktown Heights, New York. The son of a high school Earth Science teacher and a graphic designer and art director, Sam frequently pursued various ventures in science and art. In high school, Sam participated in the New York State high school science research program through SUNY Albany, and conducted two original research projects over four years: a marine seismology project conducted at the Lamont-Doherty Earth Observatory and a glaciology project conducted with the Juneau Icefield Research program in Alaska. When he wasn't doing science research, Sam regularly performed in his high school jazz ensemble and the theater troupe. Sam graduated third in his class from Lakeland High School in 2012.

Sam came to Cornell University the following fall to pursue a degree in Science of Earth Systems. He did not stray from his performing background though, and quickly joined the Whistling Shrimp Improvisational Comedy Group. Sam was also a member of CU Nooz, Cornell's satirical online newspaper, and the Science of Earth Systems Student Association. Following his sophomore year, Sam was an intern at Scripps Institution of Oceanography in San Diego, CA. In the spring of his junior year, Sam participated in the Sea Education Association (SEA) Semester program, during which he sailed from New Zealand to Tahiti. Sam finished his undergraduate work a full year earlier than expected, graduating Magna Cum Laude with a B.S. in Science of Earth Systems and a minor in Marine Biology in 2015.

Sam didn't leave Cornell however, staying as a Master's student under the guidance of Dr. Chuck Greene and Dr. Bob Howarth. Sam participated in the Summer Student Fellowship at the Woods Hole Oceanographic Institution in 2015, and was a Hudson River Foundation Polgar

Fellow the following year. Sam has been a teaching assistant (TA) for multiple oceanography classes at Cornell, including managing the undergraduate TA's for the Introduction to Oceanography class, the largest class at Cornell.

ACKNOWLEDGEMENTS

There are so many people that I need to thank for helping with my research, starting first and foremost with my thesis committee members, Dr. Chuck Greene and Dr. Bob Howarth. Chuck approached in me in the fall of my junior year and offered to be my advisor. In our first official meeting, he proposed that I graduate a year early to pursue a Master's degree under his guidance. I was amazed that someone who had only known me for a few hours would be willing to offer me something so major for both my academic and future career. And thus, I ended up graduating that spring and suddenly beginning as a graduate student the following fall. Chuck was the reason I pursued this opportunity, and without him I don't know where I'd be today.

Bob gave a guest lecture in one of my classes the spring of my sophomore year. I found the research to be pretty interesting, and approached him after class to ask if I could do research with him. Much to my surprise, he said he might have a project for me. Bob allowed me to sit in on meetings and discussed potential projects with me despite having just met me, preparing me for a likely senior honors thesis. When I decided to graduate early to start my graduate work, I knew I still wanted to continue working with Bob, and he set the stage for me to expand that senior honors thesis into a Master's thesis. Along the way, Bob has given me so much support and gave me the confidence to keep pushing on through difficult times. Again, I cannot thank Chuck and Bob enough for trusting me and giving me this incredible opportunity.

Although not a committee member, it's fair to say that Dr. Bruce Monger was an honorary committee member and advisor of mine throughout my five years at Cornell. I met Bruce when I visited Cornell as a high school senior. He said that he wanted to make Introduction to Oceanography the biggest class at Cornell, which I pretty much scoffed at.

When I took the class in my freshman year, it was still in Kennedy Hall, but sure enough, a few years later it was moved to Bailey Hall due to overwhelming demand and became the largest class at Cornell. I have taken all three of Bruce's offered classes, have been an undergraduate teaching assistant for his classes twice, and a graduate teaching assistant for his classes three times. Bruce is one of the most kind and caring professors I've ever met or worked with, showing a clear passion for what he believes in and a desire to treat everybody fairly. He makes the classroom and workspace fun and enjoyable, and after teaching thousands of students about various environmental issues and what they can do to make a difference, I have no doubt that Bruce has made a substantial impact on not only the student body of Cornell but the world as a whole. I will sincerely miss having an office that neighbors his and hearing his numerous stories for the second or third time.

As far as my own officemates go, I was very lucky to share an office with Dr. Erin Meyer-Gutbrod, Sage Mitchell, Margaret Daly, and multiple undergraduate researchers. All of these people have helped keep me sane over the years, from listening to me practice my thesis defense talk to joking around. Without them, I would likely have had a much different and a lot less fun graduate experience. Erin also taught me how to drive a manual car.

I would like to thank the various researchers that have helped me with this thesis: Dr. Dr. Rocky Geyer of Woods Hole Oceanographic Institution, Dr. John Wilkin of Rutgers University, Dr. Tao Wang of Woods Hole Oceanographic Institution, Dr. Dave Ralston of Woods Hole Oceanographic Institution, Dr. Jacqueline McSweeney of Rutgers University (now at Scripps), and Dr. Stuart Findlay of the Cary Institute of Ecosystem Studies. I also want to thank the other researchers and teachers who have offered me incredible research opportunities over

my high school and collegiate career, and who have encouraged me to continue pursuing science: Dr. Matthew Pritchard of Cornell University, Dr. Dave Chadwell of Scripps Institution of Oceanography, Dr. Maya Tolstoy of Lamont-Doherty Earth Observatory, Mr. Michael Lillis of Lakeland High School, and Ms. Madeleine Ferren of Lakeland High School. I have learned nearly everything I now know about research from these incredible people and have been so lucky to have worked with all of them. I would also like to thank various funding sources, including the Marine Physical Laboratory Internship at the Scripps Institution of Oceanography, the Summer Student Fellowship at the Woods Hole Oceanographic Institution, the Polgar Fellowship from the Hudson River Foundation, the Donovan Family Scholarship, and the Cornell Travel Grant.

Last, but far from least, I would like to thank my family and friends. My family has supported me in every project I have undertaken, which although seems simple, is one of the greatest services a family can provide. Throughout years of struggles, I knew I could always call home and talk to someone who believed in me and gave me the strength to continue. So thank you to all of my family members, I love you all. And thank you to my friends, who were always there to help despite sarcasm that would suggest otherwise. From the Whistling Shrimp to J3 to CU Nooz to my high school friends and all the friends in between, I am so lucky to have you all on my side. I would like to explicitly not thank Jake Potashnick, who has made fun of my research for the past five years and has done nothing to help.

I am somewhat bad at acknowledgements, but I hope that I have made it abundantly clear that without the people mentioned, along with a lot of others that I probably forgot to mention, I would not be where I am today. Thank you all again.

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1 INTRODUCTION

The Hudson River Estuary (HRE) is the most nutrient loaded estuary in the United States relative to its area, due to high levels of input from wastewater, urban discharges, and agriculture throughout the upper watershed (Howarth et al. 2006). Yet despite these favorable nutrient conditions, phytoplankton blooms within the estuary have not been observed (Howarth et al. 2000). Nearby phytoplankton blooms in the lower New York (NY) Harbor, NY Bight, and Long Island Sound, as well as low levels of measured chlorophyll-a within the HRE, indicate that phytoplankton can grow within the confines of the estuary; however, the exact mechanisms limiting extensive growth, including light availability, residence time, and variance within the spring-neap tidal cycle, are not well understood (Malone 1976, Malone 1977, Howarth et al. 2006).

Howarth et al. (2000) suggested that water residence time within the shallow euphotic zone of the HRE was too low to sustain growth, as phytoplankton were flushed out of the estuary before blooms could occur. The annual average discharge rate in the HRE is typically 550 m^3/s, however the average discharge rate during the summer drops to 200 m^3/s (Ralston et al. 2012; Geyer and Ralston 2015). Gross primary production (GPP) within the estuary has been observed to increase as the river discharge rate decreases during these summer months (Howarth et al. 2000), occasionally entering near-bloom conditions (data taken from the NYC DEP, accessible via http://www.nyc.gov/html/dep/html/harborwater/harbor_water_sampling_results.shtml). This summer discharge rate is expected to decline in future decades with a potential minimum summer discharge rate of 50 m^3/s, as predicted by watershed modeling using IPCC climate assessments for the Hudson River region (Swaney et al. manuscript in prep.).

A consistent slowing down of the river may then provide the necessary conditions to allow phytoplankton to bloom within the HRE, as residence time may increase in response to slower discharge rates.

The residence time of water within the euphotic zone of the HRE has previously been calculated using the Pritchard method (Pritchard 1969) to be approximately one day, a relatively low value due to a large drainage basin compared to the area of the estuary (Howarth et al. 2000, Howarth et al. 2006). Age, which can be considered a compliment to and proxy for estuary residence time (Takeoka 1984), can more accurately assess the movement of water within river and estuary systems than broad full-estuary residence time calculations alone (Deleersnijder et al. 2001; Shen and Hass 2004). A real-time three-dimensional numerical model can be used to calculate freshwater and saltwater age as a function of river discharge rate and other environmental conditions.

In this study, we used the Regional Ocean Modeling System (ROMS) (Shchepetkin and McWilliams 2005) to model simplistic and idealistic phytoplankton growth and age at current summer average and projected minimum summer average discharge rates, 200 m^3/s and 50 m^3/s respectively, in an attempt to determine if diminished summer discharge rates over an extended period of time would result in extensive phytoplankton growth within the HRE. The goals of this study were to assess the likelihood of, and if possible, the necessary conditions for, a phytoplankton bloom in the HRE in future decades, as well as to relate trends in phytoplankton growth with associated trends in saltwater age distribution.

2 METHODS

2.1 Site Description

The Hudson River is a major waterway in New York state, emptying into the NY Harbor and eventually into the NY Bight (Figure 1). The tidal extent of the river is 240 km north of the southern tip of Manhattan, while the northward limit of the HRE as defined by the 1 psu halocline typically ranges from 30 km to 100 km up-river but can reach as far north as 140 km (Abood 1974; de Vries and Weiss 2001). The average summer discharge rate of the river is 200 m^3/s (Abood 1974), however this value is expected to drop to as low as 50 m^3/s in future decades, based on Hudson watershed models using IPCC climate projections (Swaney et al.

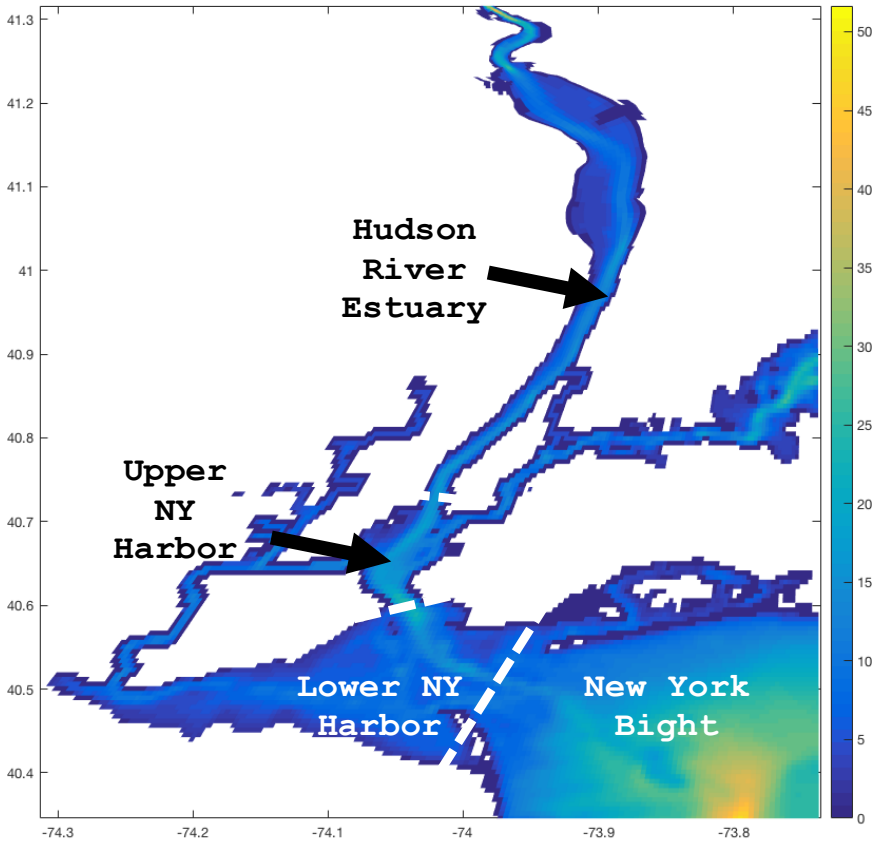


Figure 1: The depth (m) of the lower portion of the model domain and Hudson River, outlining the divisions of the various locations within the river and harbor that are used in this study.

manuscript in prep.). The Hudson River is a relatively turbid system, frequently with a euphotic zone depth of 5 m or less for the river and NY Bight but often lower within the HRE (Malone 1977, Howarth et al. 2000).

2.2 Numerical Model

The Regional Ocean Modeling System (ROMS) was used to simulate realistic river conditions in a previously established Hudson River domain (Warner et al. 2005; Ralston et al. 2012). The Hudson River topography, tidal forcing, and sediment concentration and distribution were based off of Ralston et al. (2012), however model resolution was reduced by a factor of 3 in both horizontal directions to allow for faster model runs. For model runs that included biology, phytoplankton were introduced into the model following 30 days of running the model at 500 m^3/s to allow sediment to become well mixed within in the water column after multiple spring-neap tidal cycles. Subsequent model runs included a river discharge rate of either 200 m^3/s or 50 m^3/s.

The underwater light environment for the model was developed using *in situ* light attenuation and sediment data, collected at Haverstraw Bay over a 30-year period (data taken from Cary Institute of Ecosystem Studies, accessible via http://www.caryinstitute.org/science-program/research-projects/hudson-river-ecosystem-study/hudson-river-ecosystem-study-data). A simple linear model was created to relate the light attenuation coefficient (K_d) to suspended sediment concentration (SSC), which yielded the equation $K_d = 1.44 + 0.039(SSC)$ (Figure 2). Attenuation due to seawater, chlorophyll, detritus, and dissolved organic matter (DOM) are considered to be included within the first term of this equation, as these parameters

were not included in our model and have previously been determined to comprise a relatively small portion of the total attenuation for the HRE (Malone 1976). This equation likely overestimates light attenuation for the lower NY Harbor and NY Bight, where water clarity tends to be much higher and blooms have previously been observed (Malone 1976, Mahoney and McLaughlin 1977, Malone 1978). Using a similar linear model, Malone (1976) demonstrated a relationship between K_d and SSC with a comparable slope but far lower intercept (0.03, compared to 1.44 in our linear model). Regardless of this possible

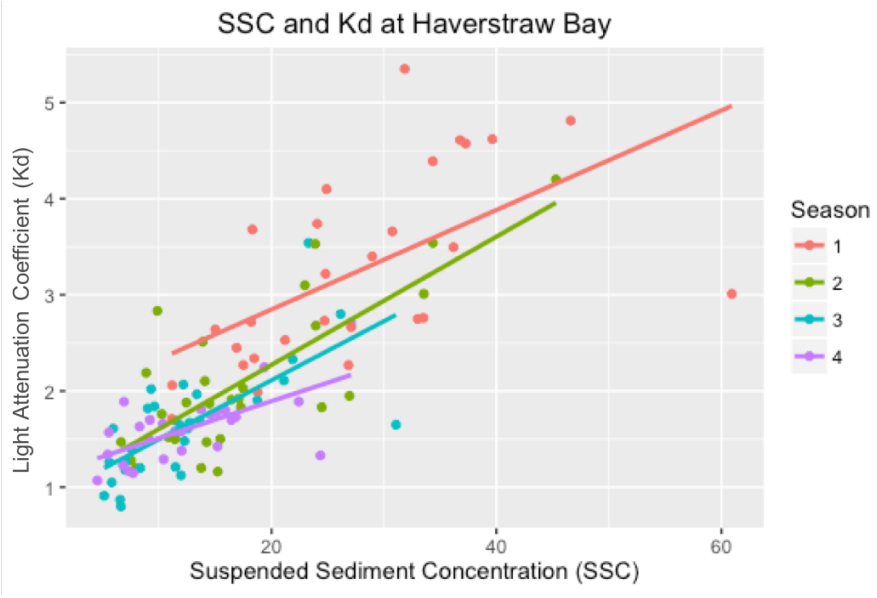


Figure 2: Light attenuation Coefficient (K_d) compared to Suspended sediment concentration (SSC) data for all seasons (Season 1 = winter, Season 2 = spring, Season 3 = summer, Season 4 = autumn) taken from Haverstraw Bay in the HRE. No statistically significant difference was found between seasons, and therefore the entirety of the data set was used to calculate the equation $K_d = 1.44 + 0.039(SSC)$. Data was provided by the Cary Institute for Ecosystems Studies.

overestimation of light attenuation for these southern regions, this study focuses primarily on estimating accurate growth within the estuary and not beyond upper NY Harbor.

Light attenuation was represented in the biological model as the percentage of surface light available at a certain depth as used in Fennel et al. (2006) and McSweeney et al. (2016). As

previously described, K_d was calculated entirely from SSC, and our model did not include the individual attenuation parameters related to seawater or chlorophyll as done previously in the other studies mentioned. Percentage of light availability was calculated at each depth level of the model based on K_d and was decreased exponentially with depth. Using an equation to relate light attenuation to euphotic zone depth (Kirk 1994) and our linear model for light attenuation, it was determined that growth would be primarily limited to a maximum depth of 3.2 m of the water column, with shallower euphotic zone depths when sediment was present in the water column (as calculated by the equation presented in Figure 2).

The biological model used was based off of the model described in Franks et al. 1986, and was highly idealized to create favorable bloom conditions. We focused on phytoplankton growth, and zooplankton, detritus, and DOM concentrations were not explicitly modeled. Nutrient levels were set explicitly high and remained unchanged throughout model runs to simulate the high nitrogen concentrations in the HRE where nutrient limitation is highly unlikely to occur. The maximum phytoplankton growth rate was set to 1.15 d^{-1}, a relatively high growth rate for marine systems and an above average growth rate for an estuary system (Brand 1984; Calbet and Landry 2004). This growth rate is comparable to the marine flagellate species *Olisthodicus luteus*, known to grow and occasionally bloom in nearby Lower NY Harbor, Narragansett Bay, and Long Island Sound (Lackey 1963; Mahoney and McLaughlin 1977; Tomas 1978). This species has previously been shown to have harmful effects on its surrounding environment, including killing marine bacteria and potentially damaging fish populations (Kim et al. 1999). Using *O. luteus* as a representative species, growth was modeled as a step function of salinity, based off of the salinity tolerances presented in Brand (1984). The initial

phytoplankton population was set universally throughout the model domain and the population value was based on the lower end of observed chlorophyll-a concentrations for the majority of the model runs (data from the Cary Institute of Ecosystem Studies, accessible via http://www.caryinstitute.org/science-program/research-projects/hudson-river-ecosystem-study/hudson-river-ecosystem-study-data). An additional model run included a much higher initial chlorophyll concentration within the model, based on the higher chlorophyll-a concentrations observed within the HRE, run at 50 m^3/s. General zooplankton grazing and phytoplankton mortality were combined in a single term, which equaled 0.05 d^{-1}. This value is within the range of observed zooplankton grazing for the HRE (within 0.1% and 6.6% of phytoplankton grazed by the dominant zooplankton species during the summer months; Lonsdale et al. 1996) and is less likely to constrain phytoplankton growth than the mortality rate of 0.1 d-1 used in the original Franks et al. (1986) study. Franks et al. (1986) concluded that the model is not very sensitive to changes in mortality rate.

We implemented two types of age tracers in the model: a freshwater tracer introduced at the northern boundary of the model domain, and a saltwater tracer introduced at the southern and eastern boundaries of the model domain. Each tracer had two components, a tracer concentration *C* and an age concentration α based on the work of Deleersnijder et al. (2001) and Shen and Haas (2004). The tracer concentration of *C* is the integral of the concentration distribution function $c(t,x,\tau)$ that was introduced by Deleersnijder et al. (2001), which itself represents the distribution of a material based on the time *t*, the space *x*, and the age of the material since entering the system τ. *C* can be calculated with the equation $C(t,x) = \int_0^\infty c(t,x,\tau)d\tau$. Using a similar equation, the age concentration α can also be calculated:

$\alpha(t,x) = \int_0^\infty \tau c(t,x,\tau) d\tau$. The mean age of a parcel of water is then calculated using these two tracer components: $a(t,x) = \frac{\alpha(t,x)}{C(t,x)}$, or the ratio of age concentration to the total concentration. The result of this calculation does not represent the concentration of tracer present at a particular location but instead the age of however much tracer is present. Freshwater age can be used to better visualize downstream advection and determine how long surface water may stay within the estuary, and saltwater age can be used in this scenario to monitor the movement of marine phytoplankton after entering the estuary from the ocean (or, in our case, the southern and eastern boundaries of the model). Freshwater age tracers were adjusted to equal zero for salinity values lower than our minimum salinity boundary for phytoplankton growth, or approximately 5 psu. By doing so, the actual age values between different discharge cases can be directly compared, as opposed to the saltwater age values, for which the comparison of trends are the main focus. The resulting freshwater age represents the age of freshwater after entering this region of possible growth.

Age models were run for 120 days at 200 m^3/s and 50 m^3/s to ensure that saltwater age was well distributed within the full estuary. For both saltwater and freshwater ages, it must be noted that once a tracer enters the model domain, it will continue to accumulate age over time as long as the tracer remains within the model domain. For example, a parcel of water at location X with a freshwater age of 20 days indicates that the saltwater at location X has been in the model domain for an average of 20 days. If that parcel of water remains at location X and does not mix with any younger or older water for another 10 days, the resulting freshwater age at location X will be 30 days. If the parcel is mixed with younger water, or is flushed out of the model domain entirely, the freshwater age taken from location X may be well below 20 days.

Age values calculated at various points in the tidal cycle do not represent the change in age between a spring tide and the following neap tide, but instead are used as a proxy to determine how changes associated with the tides, such as stratification or velocity structure, may impact the movement of freshwater and saltwater independently. Therefore, age values greater than the duration of time between a full spring-neap tidal cycle are to be expected, and the differences in age structure during a specific neap and spring tide will be examined for each discharge case.

3 RESULTS

Surface phytoplankton growth within the HRE was found to be generally greater when the model was run at 50 m^3/s than when the model was run at 200 m^3/s (Figure 3). This was true for all points within the spring-neap tidal cycle, with the most growth occurring during neap tides. After 30 days, there was almost no growth beyond the initial phytoplankton population occurring within the upper NY Harbor for both discharge cases, and minimal growth beyond the initial population occurring within the HRE only for the 50 m^3/s discharge case. Phytoplankton growth within the HRE never exceeded 150% of the initial population over the course of the 30-day model runs.

The model run with high initial chlorophyll concentration showed nearly identical relative chlorophyll distributions in the HRE as the model runs with lower chlorophyll concentrations (Figure 4). Similar to the low initial concentration runs, growth never exceeded 150% of the initial population.

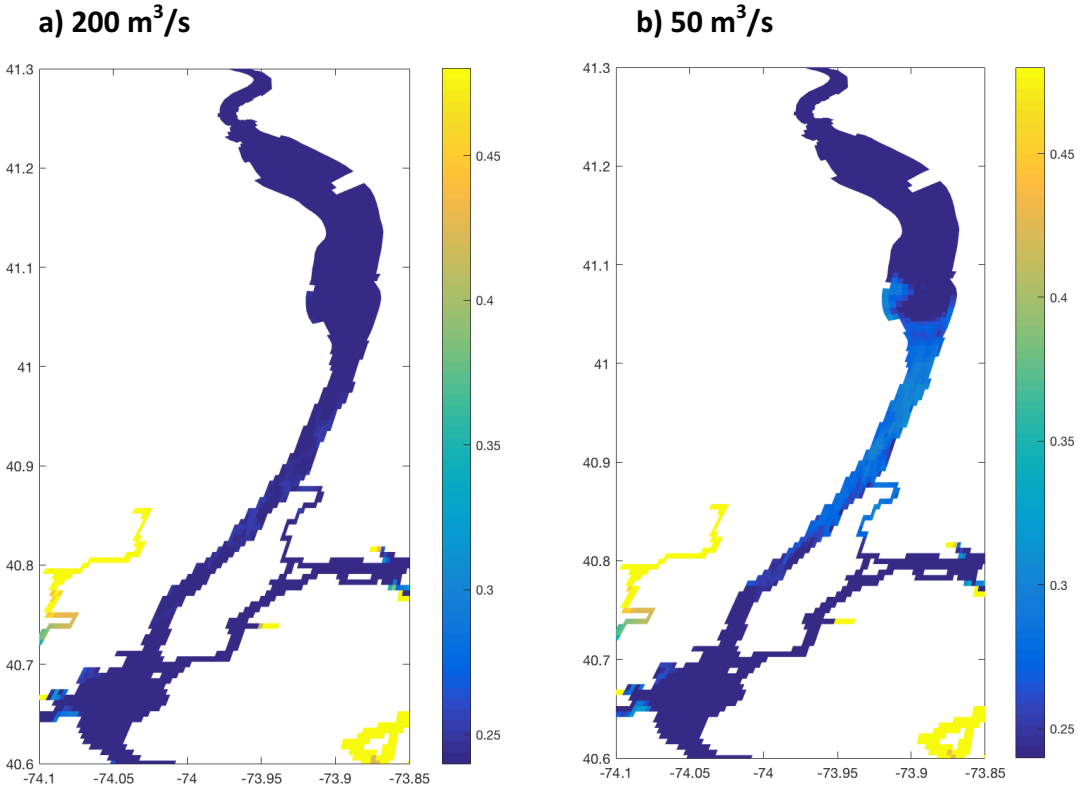


Figure 3: Surface chlorophyll-a concentration (in mg/m^3) within the HRE and upper NY Harbor after 30 days for the (a) 200 m^3/s discharge case and the (b) 50 m^3/s discharge case during a neap tide. The color scale is set from the initial population to twice the initial population.

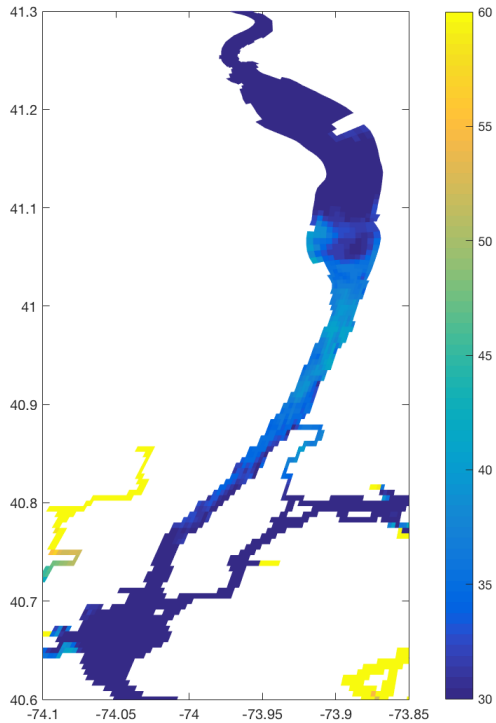


Figure 4: Surface chlorophyll-a concentration (in mg/m^3) within the HRE and upper NY Harbor after 30 days for the 50 m^3/s discharge case, from the high initial chlorophyll concentration run. The color scale is set from the initial population to twice the initial population.

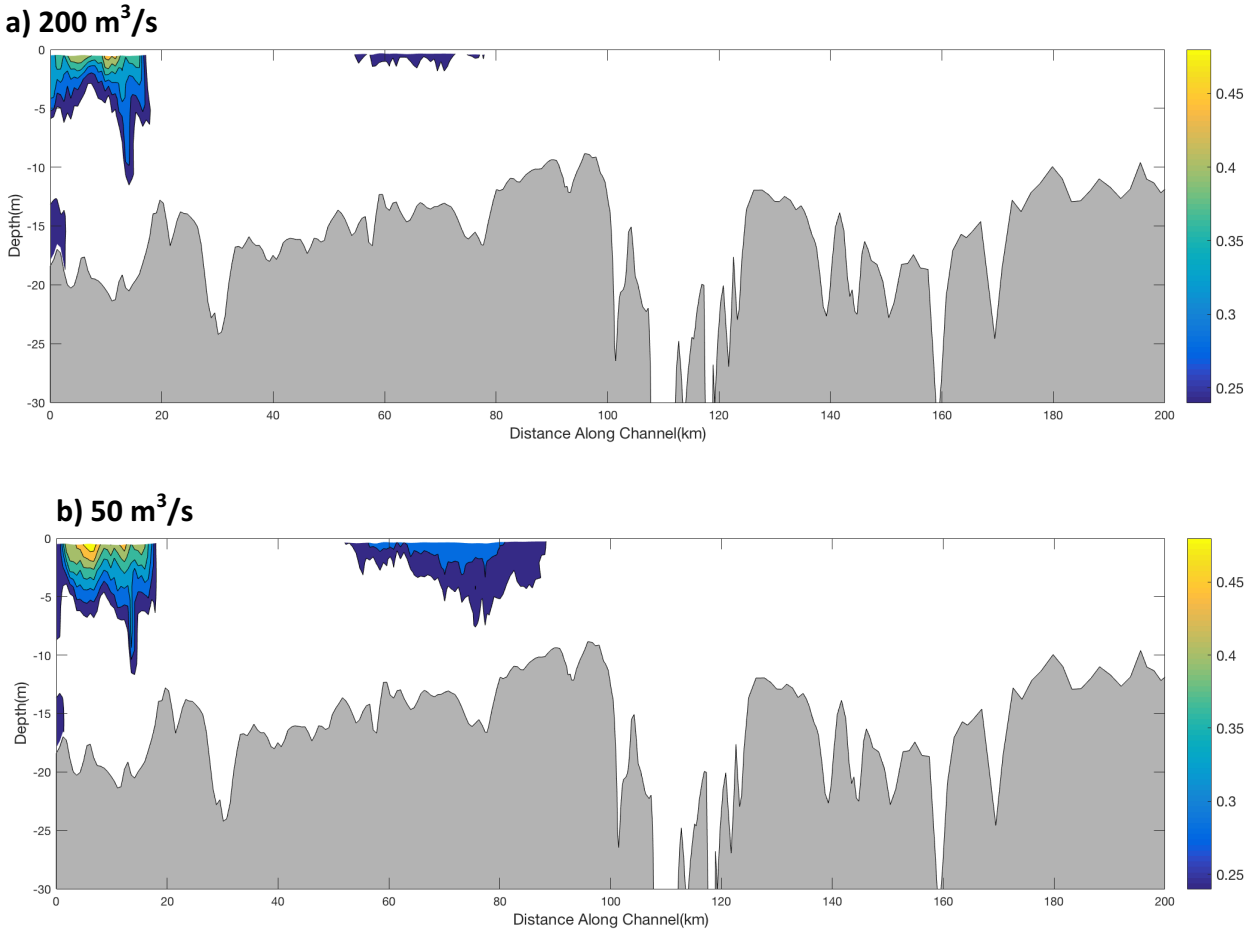


Figure 5: Cross-sectional chlorophyll-a concentration (in mg/m^3) along the thalweg of the model domain during a neap tide, from 0 km to 200 km up-river, for the (a) 200 m^3/s discharge case and the (b) 50 m^3/s discharge case. Areas of white do not indicate that there is no chlorophyll present, but instead are areas where chlorophyll did not exceed the initial chlorophyll concentration. The southern extent of the HRE can be considered to be located at the 42 km marker.

Chlorophyll concentrations within the water column that are equal to or exceed the initial concentration are also presented along the thalweg of the river for neap and spring tides for each discharge case (Figure 5, 6). This cross-sectional view shows significant growth occurring within the NY Bight and lower NY Harbor, as well minimal growth in the lower portion of the HRE (which begins at approximately the 42 km marker in the cross-sectional figures and

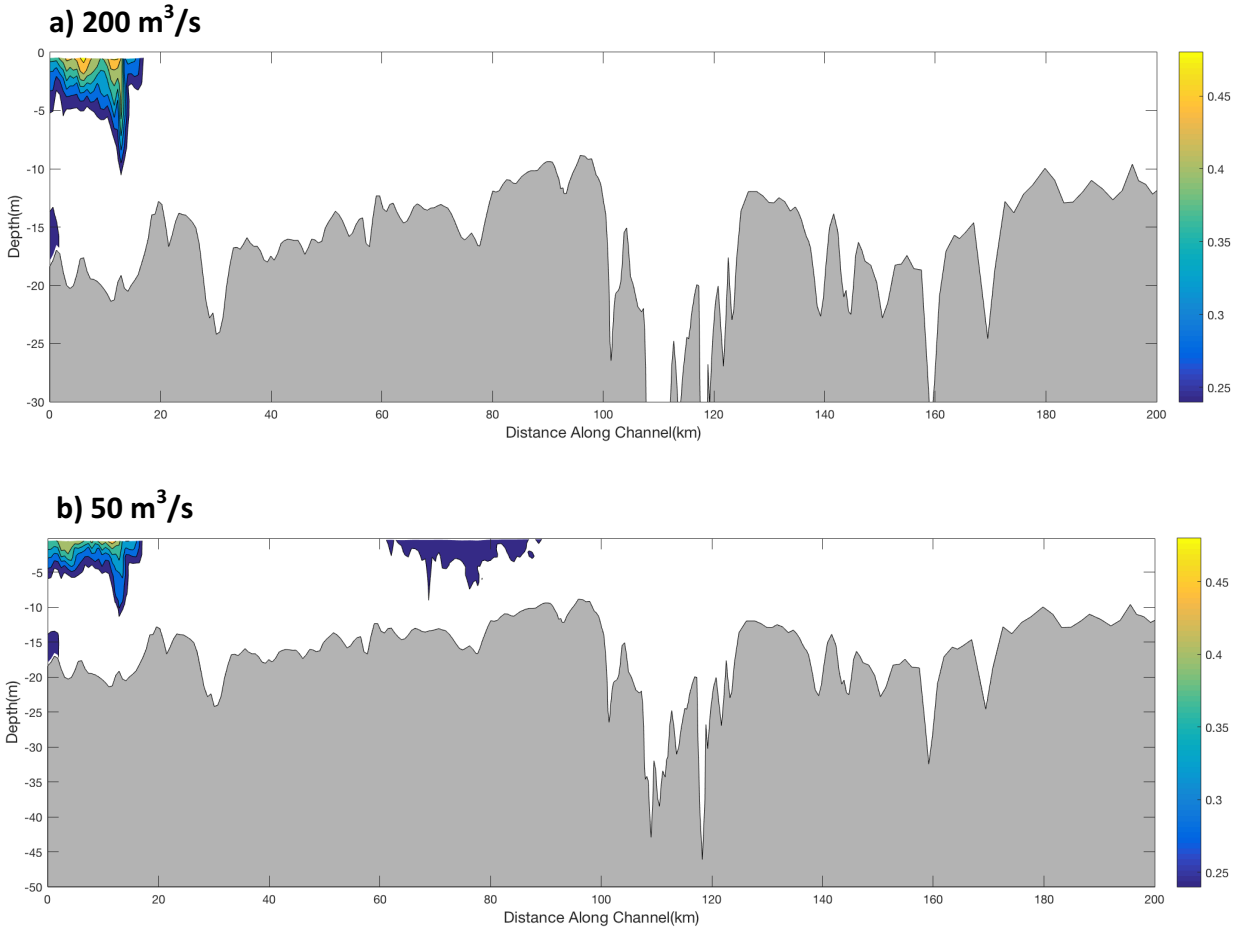


Figure 6: Cross-sectional chlorophyll-a concentration (in mg/m^3) along the thalweg of the model domain during a spring tide, from 0 km to 200 km up-river, for the (a) 200 m^3/s discharge case and the (b) 50 m^3/s discharge case. Areas of white do not indicate that there is no chlorophyll present, but instead are areas where chlorophyll did not exceed the initial chlorophyll concentration. The southern extent of the HRE can be considered to be located at the 42 km marker.

extends northward), for both discharge cases. Again, growth was generally greater during neap tides relative to spring tides, as well as during the 50 m^3/s case relative to the 200 m^3/s case.

Freshwater ages within our established region of approximately 5 psu or greater increased for the 50 m^3/s case relative to the 200 m^3/s (Figure 7, 8) This is expected, as the water will spend more time within the model boundaries under slower discharge conditions. After running the model for 120 days, freshwater ages at the surface of the water column

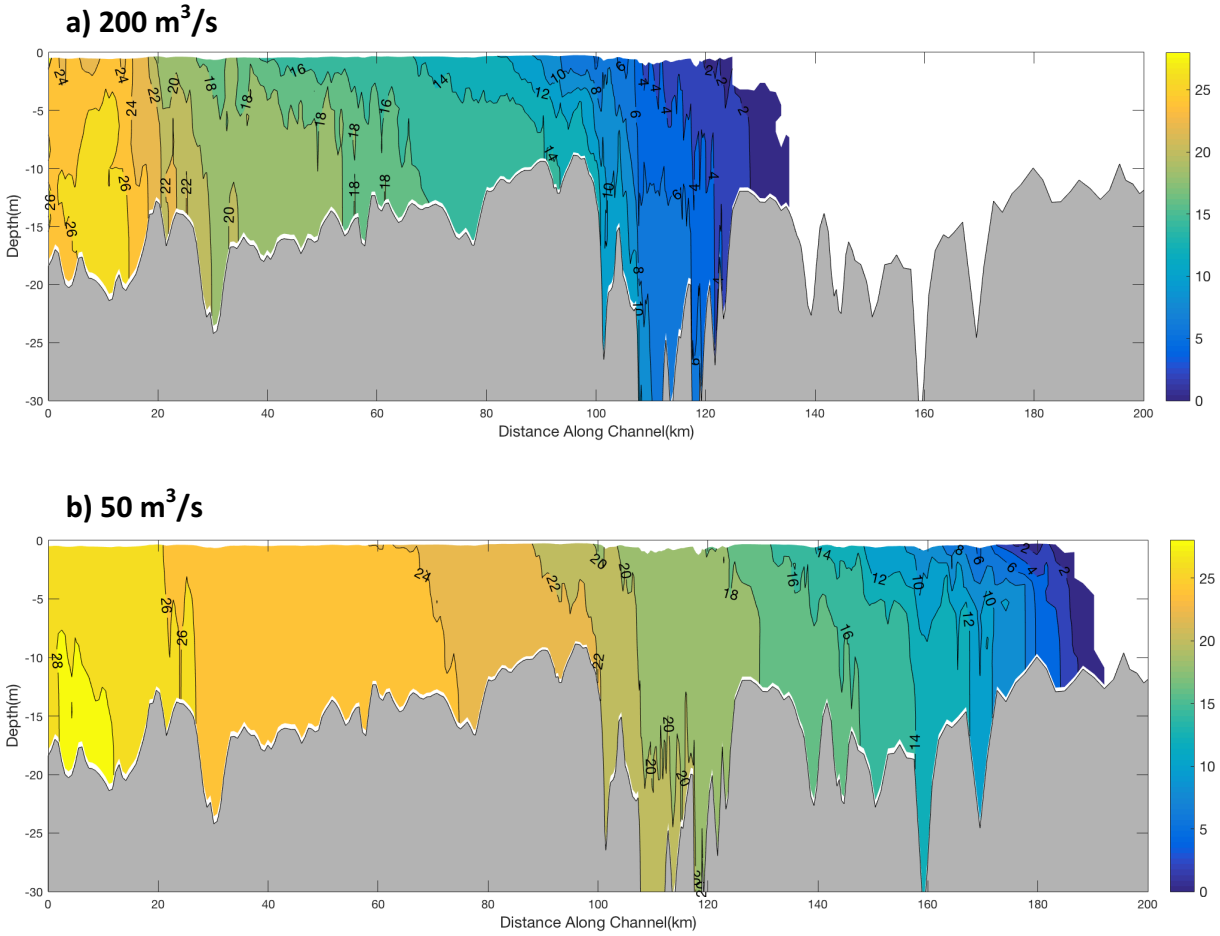


Figure 7: Cross-sectional freshwater age structure (in days) along the thalweg of the model domain during a neap tide, from 0 km to 200 km up-river, for the (a) 200 m^3/s discharge case and the (b) 50 m^3/s discharge case. Freshwater age values begin at approximately the 5 psu salinity contour and age normally beyond that point.

increased from 16 to 25 days between the 200 m^3/s and 50 m^3/s discharge cases, respectively, during a neap tide between the northward extend of the established salinity range and the southern end of the estuary, or at 42 km in figure 7. During a spring tide, the age at that same location was 18 days for the m^3/s discharge case, an increase relative to the neap tide. For the 200 m^3/s case, the age at that location during the spring tide was 23 days, a decrease relative to the neap tide.

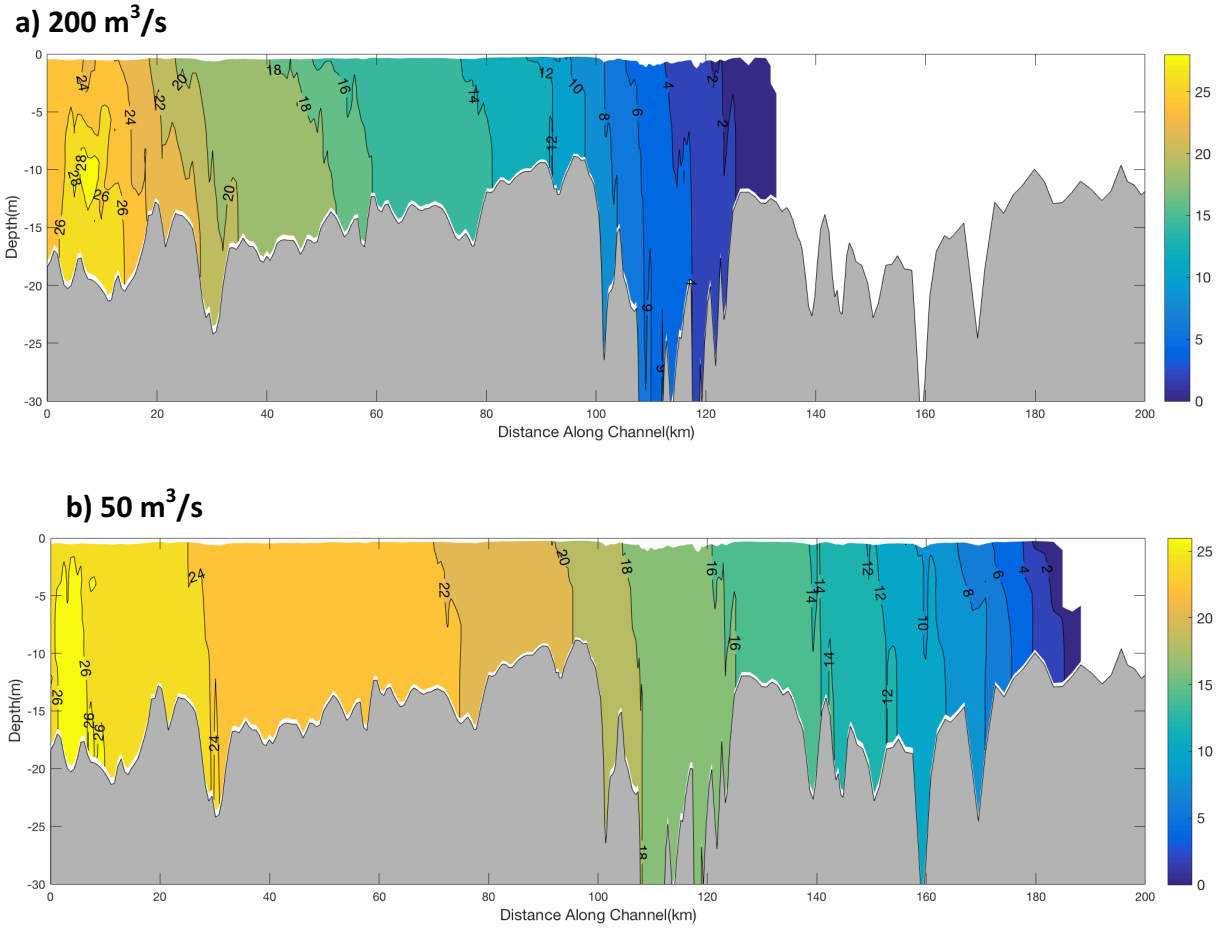
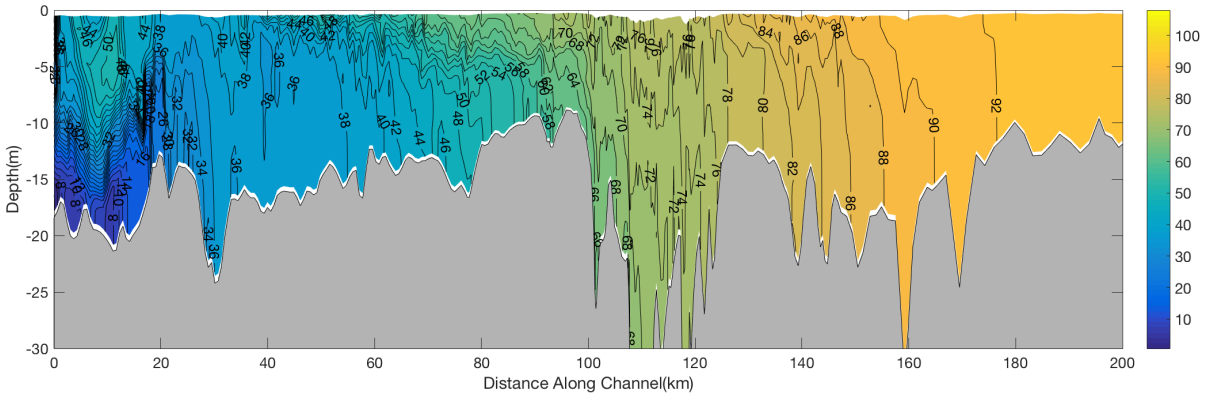


Figure 8: Cross-sectional freshwater age structure (in days) along the thalweg of the model domain during a spring tide, from 0 km to 200 km up-river, for the (a) 200 m^3/s discharge case and the (b) 50 m^3/s discharge case. Freshwater age values begin at approximately the 5 psu salinity contour and age normally beyond that point.

The saltwater age tracer followed a similar trend as salinity within the majority of the model domain, but differed greatly within the NY Bight (Figure 9, 10, 11, 12). Age values were greater during the 50 m^3/s case as opposed to the 200 m^3/s case, which is expected; slower discharge rates will allow for water to spend more time within the model boundaries, and for saltwater, allow the tracer to expand further up-estuary. Stratification patterns of the HRE within the spring-neap tidal cycle for the 200 m^3/s discharge case were consistent with patterns previously reported and observed in the same region (MacCready and Geyer 2009). For the 50

a) 200 m^3/s



b) 50 m^3/s

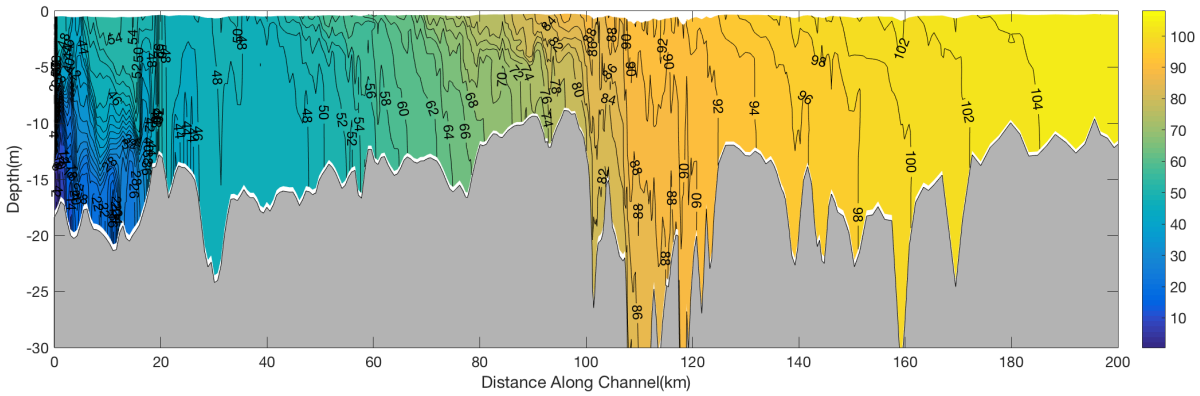


Figure 9: Cross-sectional saltwater age structure (in days) along the thalweg of the model domain during a neap tide, from 0 km to 200 km up-river, for the (a) 200 m^3/s discharge case and the (b) 50 m^3/s discharge case.

m^3/s discharge case, stratification during neap tides was lessened relative to the 200 m^3/s discharge case, as observed in both salinity and saltwater age distribution. During spring tides, when the water column is already expected to be mixed, there was no significant difference in stratification between the two discharge cases, and therefore we will be focusing primarily on the neap tide. For the 200 m^3/s discharge case, a difference of 10 psu between the surface and bottom of the water column was observed at 30 km up-estuary (or approximately the 60 km marker in the cross-sectional figures) during a neap tide, while the 50 m^3/s discharge case showed a difference of only 2 psu for the same time and location (Figure 11). For the saltwater age results, a difference in saltwater age between the surface and bottom of the water column

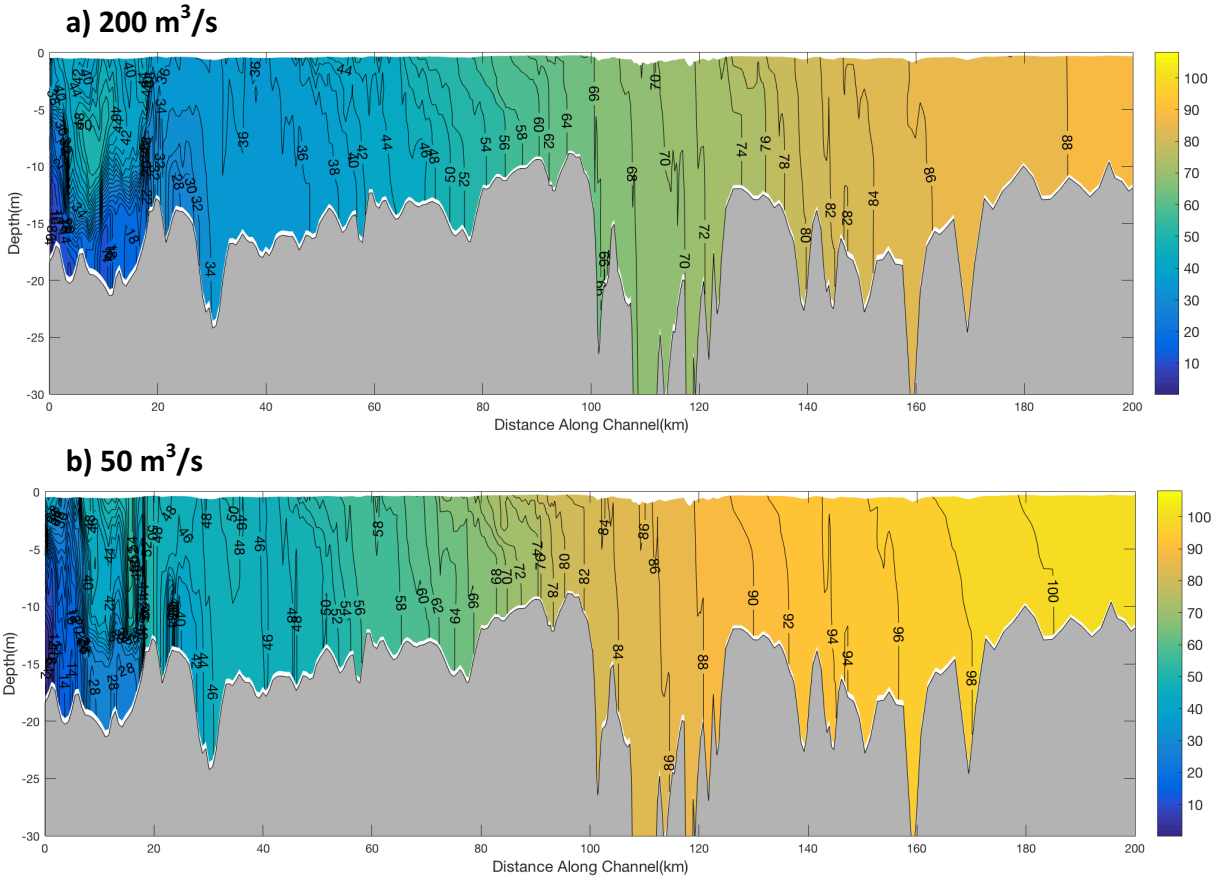


Figure 10: Cross-sectional saltwater age structure (in days) along the thalweg of the model domain during a spring tide, from 0 km to 200 km up-river, for the (a) 200 m^3/s discharge case and the (b) 50 m^3/s discharge case.

of 13 and 6 days was observed at the same time and location as the salinity results for the 200 and 50 m^3/s discharge cases, respectively (Figure 9), despite overall greater age values for the slower case. Both discharge cases show a trend of increasing saltwater age with increasing distance along the thalweg of the river, with the exception of the NY Bight, where a region of high age values was found near the surface of the water column.

4 DISCUSSION

No phytoplankton blooms were observed at any point in the spring-neap tidal cycle for either modeled discharge case. Although minimal growth beyond the initial concentration was

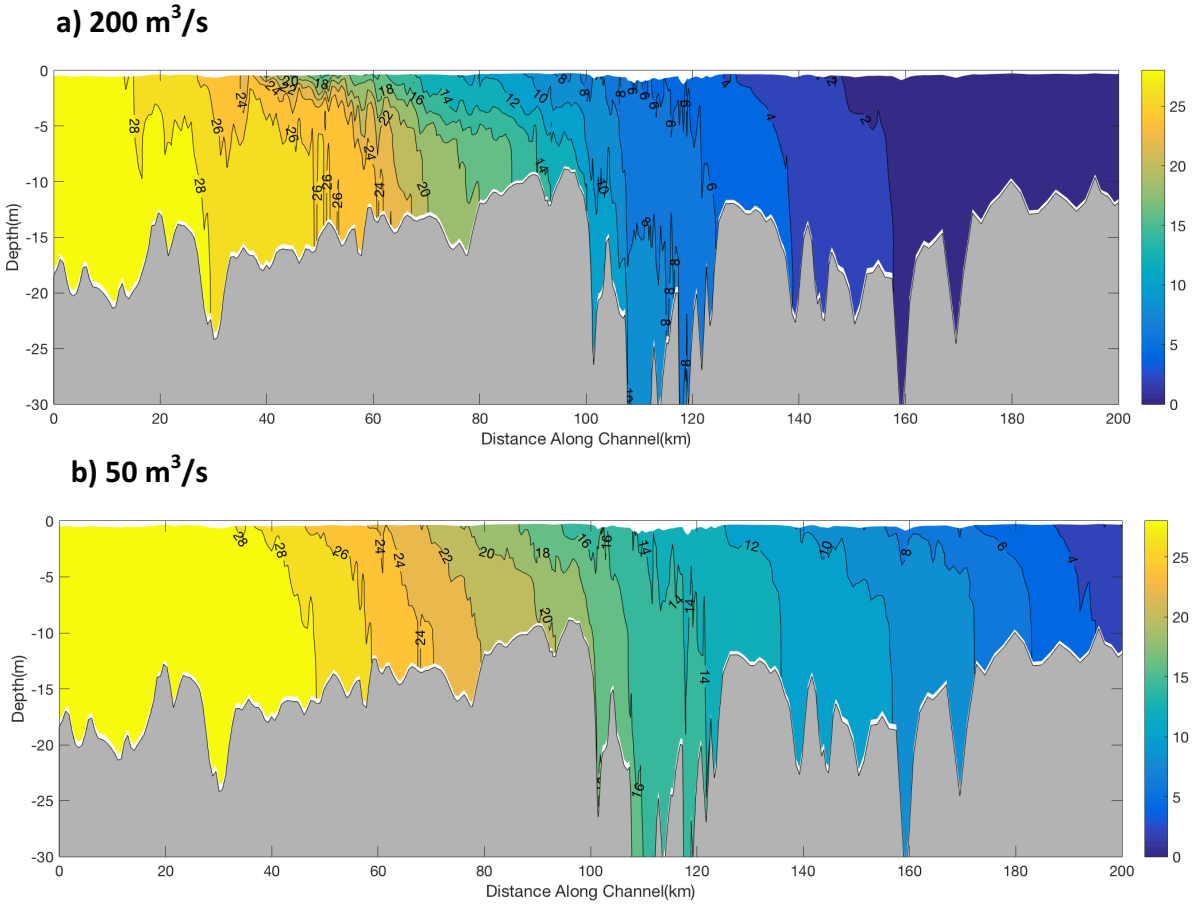


Figure 11: Cross-sectional salinity structure (in psu) along the thalweg of the model domain during a neap tide, from 0 km to 200 km up-river, for the (a) 200 m^3/s discharge case and the (b) 50 m^3/s discharge case.

observed for the 50 m^3/s case, the magnitude of this change in chlorophyll concentration is not enough to classify it as a bloom. As a point of comparison, previous phytoplankton blooms in the NY Bight and Chesapeake Bay were much greater in magnitude and population growth far exceeded what we observed in these model runs (Mahoney and McLaughlin 1977, Gallegos and Jordan 2002). Phytoplankton growth within the lower NY Harbor and NY Bight, seen in the results of each discharge case, could likely be considered blooms, though these blooms are within the regions where phytoplankton blooms have previously been observed and the

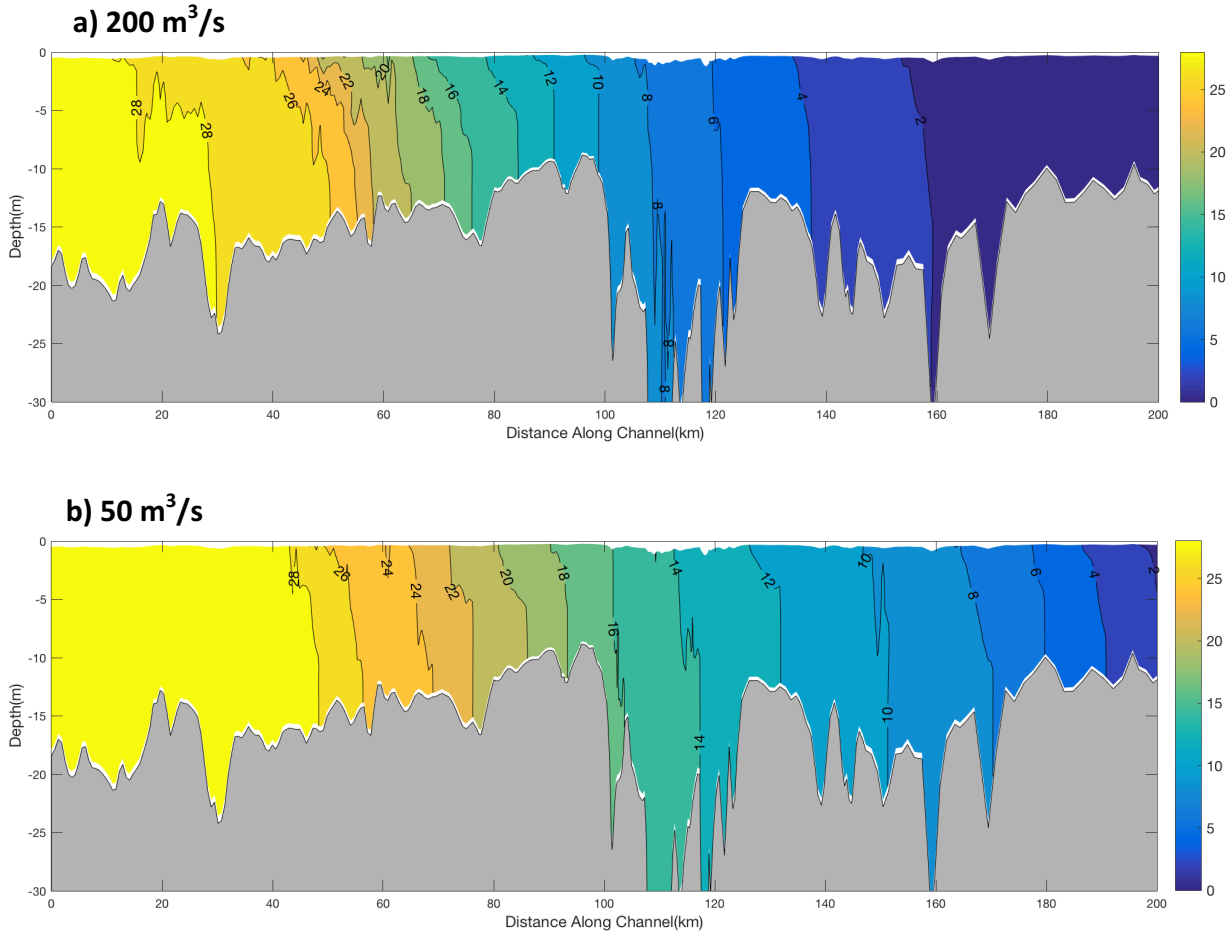


Figure 12: Cross-sectional salinity structure (in psu) along the thalweg of the model domain during a spring tide, from 0 km to 200 km up-river, for the (a) 200 m^3/s discharge case and the (b) 50 m^3/s discharge case.

magnitude of the modeled phytoplankton growth is not considered for this study beyond a doubling of the population.

The freshwater age, saltwater age, and salinity distribution all indicate increased mixing during a neap tide for the 50 m^3/s discharge case compared to the same neap tide for the 200 m^3/s discharge case, associated with decreased discharge rate and therefore tidal dominance over water movement within the estuary. The difference in mixing between discharge cases is present but less apparent for the spring tides, during which the water column is already expected to be heavily mixed. Slower discharge rates appear to increase mixing in the estuary,

which decreases stratification in the water column, as seen in changes in salinity stratification between discharge rates in Figure 11. For neap tides specifically, when chlorophyll was generally greatest within the water column for both discharge cases compared to spring tides, the lessened stratification and increased mixing observed during the 50 m^3/s case relative to the 200 m^3/s case appeared to have counteracted the growth benefits of increased age and therefore increased residence time. Although phytoplankton spent more time within the estuary under slower river conditions, as indicated by an approximately 8-day increase in surface freshwater age between discharge cases (Figure 7), phytoplankton likely did not spend an equivalent amount of time in the euphotic zone, due to a decrease in stratification from 10 psu to 2 psu. Greater stratification in the estuary water column during neap tides at 200 m^3/s would decrease the mixing depth and keep more phytoplankton within the euphotic zone; however, under these conditions, it appears that phytoplankton still did not have enough time to experience significant growth associated with blooms. The amount of time phytoplankton spent within the euphotic zone was not able to be extracted from our model, as the chlorophyll and age models did not follow explicit cells but instead calculated concentration averages at each point in the model domain. However, by observing the maximum chlorophyll concentration observed during the 50 m^3/s case (Figure 3), and calculating the minimum necessary time needed to reach that concentration using maximum growth rate (1.15 d^{-1}) and zero sediment attenuation as used in the model, we find a minimum phytoplankton residence time within the euphotic zone of approximately one day. While this residence time seems unlikely, based on much higher freshwater age values within the estuary and a high improbability of phytoplankton staying within a region of zero SSC under increased mixing

conditions, this result confirms that Howarth et al. (2000) did not underestimate their calculation of a one-day residence time for current summer discharge rates.

It is important to note that these age values represent the average amount of time elapsed since the freshwater entered the 5 psu region and not the residence time of both freshwater and saltwater within the euphotic zone, and therefore these values are not directly comparable to the residence times predicted by Howarth et al. (2000).

Overall chlorophyll concentration was consistently higher during the neap tides than the spring tides for both discharge cases, likely due to greater mixing commonly seen during spring tides. As a comparison, salinity values during a spring tide are shown for both discharge cases (Figure 9). Based on these results, it appears that the HRE is self-limiting in terms of phytoplankton blooms, as phytoplankton euphotic zone residence time would be too low to allow for blooms under any current or projected environmental discharge conditions.

The area below the upper NY Harbor was not emphasized in this study, though interesting trends in chlorophyll and saltwater age within the NY Bight region were quite apparent. High saltwater age values within the surface of the NY Bight indicate stagnation, a potential reason why elevated phytoplankton growth is observed in this area. This region also shows a noticeable difference between the saltwater age and salinity plots, as this age stratification is not apparent by observing salinity alone. Although salinity can provide an accurate view of the stratification, as would age tracers, within the estuary, high age in the NY Bight (or other regions of relatively constant salinity) as a result of stagnation would be undetected by salinity measurements alone. This shows an advantage of using age tracers over salinity to determine saltwater movement in an estuary and harbor system.

5 CONCLUSION

Phytoplankton growth within the HRE has been shown to be correlated with discharge rate; however, it appears to be less susceptible to discharge rate than previously proposed. Increased mixing associated with tidal dominance under slower discharge conditions effectively limits phytoplankton growth as residence time does, despite the fact that euphotic zone saltwater age increases under these same conditions. We created ideal conditions for phytoplankton, including a relatively low mortality rate and a relatively high growth rate, and yet no blooms were observed in any model run of our study. For these reasons, we believe it is fair to assume that no phytoplankton blooms are expected to occur within the HRE under any realistic and natural conditions.

Possible anthropogenic changes to the Hudson River environment could alter the movement of saltwater within estuary, which may create favorable conditions for phytoplankton blooms in the future. Storm barriers implemented in NY Harbor have been proposed as a possible solution for increased risk of storm surges in New York City and as a way to protect against damage similar to what was caused by Hurricane Sandy in 2011 (Aerts et al. 2014). Building storm barriers in NY Harbor may increase river residence times within the estuary and therefore allow for more significant phytoplankton growth, though the exact physical and biological impacts of any large structure built in NY Harbor are largely unknown at this time. Saltwater age and euphotic zone variation within the HRE must be considered before implementing any such storm surge solution in NY Harbor.

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